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Economic design of steel bridge decks

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Abstract

The bending moments and the torsional stiffness of trapezoidal longitudinal stiffeners are calculated according to the Pelikan–Esslinger method, neglecting the flexibility of crossbeams. In fatigue constraints, recently published experimental research results are taken into account. A computer program of the Rosenbrock mathematical programming method is used to determine the following optimum dimensions: thickness of the deck plate, thickness and heights of stiffeners and crossbeams as well as the distance between crossbeams. The optimization procedure is illustrated by a numerical example. © 1998 IIW/IIS

Keywords: Bridges; Design; Costs; Bending moment; Torsional strength; Ridigity; Stiffeners; Girders; Fatigue strength

Les moments de flexion et la rigidité en torsion de raidisseurs longitudinaux en forme de trapèze sont calculés en utilisant la méthode de Pelikan–Esslinger, end négligeant la flexibilité des poutres transversales. En ce qui concerne les contraintes de fatigue, les résultats des recherches expérimentales ont été pris en compte. Un programme informatique intégrant la méthode de programmation mathématique de Rosenbrock est utilisé pour déterminer les dimensions optimales suivantes: épaisseur de la tôle due tablier, épaisseur et hauteur des raidisseurs et des poutres transversales et distance entre poutres. La procédure d'optimisation est illustrée par un exemple numérique. © 1998 IIW/IIS

Mots clés: Ponts; Conception; moment de pliage; Resistance à la torsion; Rigidité; Raidisseurs; Poutres; Résistance à la fatigue

1. Introduction

Stiffened steel decks are important structural parts of bridges. Their welded joints can fail due to fatigue because of heavy traffic load. The fabrication cost forms the main part of the total cost, therefore it affects significantly the optimum dimensions of the deck structure. Although there are many size limitations, some dimensions can be optimized. These dimensions are as follows: thickness of the deck plate, height and thickness of stiffeners and crossbeams as well as the distance between crossbeams.

For the calculation of bending moments and the torsional stiffness of stiffeners, the Pelikan–Esslinger method is used. The formulae are relatively complicated, thus a computer method should be applied. The Rosenbrock *Hillclimb* method was efficient for this purpose. The optimization procedure is illustrated by a numerical example. It should be noted that the optimum design of bridge decks with flat stiffeners has been treated in [1]. In the present paper the case of trapezoidal stiffeners is dealt with.

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2. Calculation

2.1. Assumptions

- The deck plate is simply supported around its periphery.
- The effect of the flexibility of crossbeams on bending moments in stiffeners is neglected.
- The main bridge girder and its connections to the deck structure are excluded from the calculations.
- The self-mass is neglected, since in the governing fatigue stress range constraint it should not be considered.
- The spectrum factor in the calculation of fatigue stress range is taken as 1, the number of load cycles is 2×10^6.

2.2. The live load considered for highway bridges

We select for our numerical example as live load trucks shown in Fig. 1. According to DIN 1072 [2] a truck has two wheel loads of 50 kN and two wheel

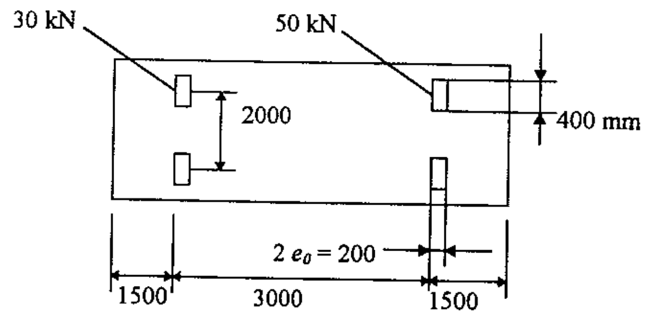

Fig. 1. Data of trucks considered as live load.

loads of 30 kN. The widths of wheels are 400 and 260 mm respectively.

2.3. *The bending and torsional stiffness of stiffeners*

The dimensions of a stiffener section are given in Fig. 2. The specific bending stiffness is defined by

$$B_y=\frac{I_y E}{a+e} \tag{1}$$

where the moment of inertia is given by

$$I_y=(a+e)t_f z_G^2+a_1 t_s (h-z_G)^2+2I_\xi+2a_2 t_s\left(\frac{h}{2}-z_G\right)^2 \tag{2}$$

with

$$I_\xi=t_s\frac{a_2^3}{12}\sin^2\alpha \tag{3}$$

and

$$z_G=ht_s\frac{a_1+a_2}{t_s(a_1+2a_2)+(a+e)t_f} \tag{4}$$

The specific torsional stiffness can be calculated by using the Pelikan–Esslinger formulae [3], which takes into account the local deformations of trapezoidal stiffeners.

$$H=\frac{\mu GT}{2(a+e)} \tag{5}$$

where

$$\frac{1}{\mu}=\frac{GT}{GT_{red}} \tag{6}$$

$$\frac{1}{\mu}=1+\frac{GT}{EI_0}\frac{a^3}{12(a+e)^2}\left(\frac{\pi}{t_2}\right)^2\left[\left(\frac{e}{a}\right)^3+\left(\frac{e-a_1}{a+a_1}+\lambda\right)^2+\frac{\lambda^2}{\kappa_0}\left(\frac{a_1}{a}\right)^3+\frac{24a_2}{\kappa_0 a}\left(c_1^2+c_1c_2+\frac{c_2^2}{3}\right)\right] \tag{7}$$

T is the torsional stiffness for a closed thin-walled section [4,5].

$$T=\frac{4A_k^2}{\sum_i (b_i/t_i)} \tag{8}$$

$$t_2=0.81t \tag{9}$$

$$EI_0=\frac{Et_f^3}{10.92} \tag{10}$$

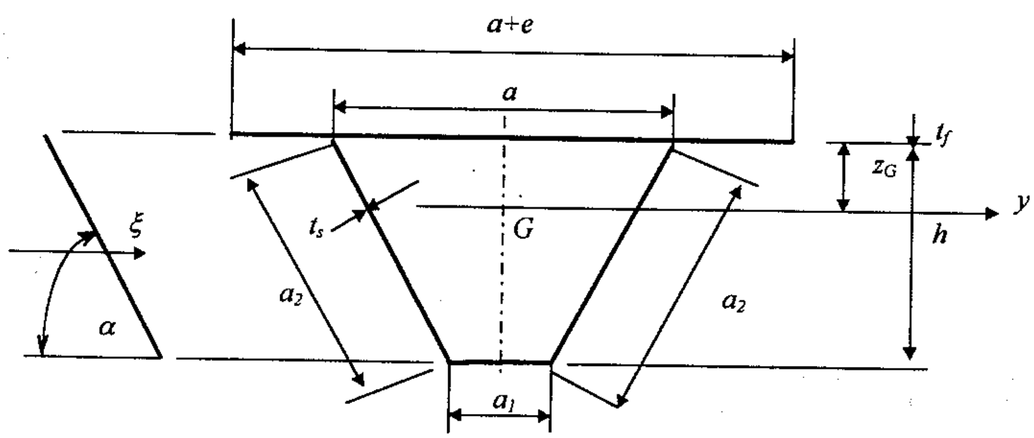

Fig. 2. Dimensions of a stiffener section.

$$A_k = h\frac{a+a_1}{2} \tag{11}$$

$$c_1 = \frac{\lambda a_1}{2a} \tag{12}$$

$$c_2 = \left(\frac{\lambda}{2}\,\frac{a-a_1}{a}\right)-\left(\frac{a+e}{a+a_1}\,\frac{a_1}{2a}\right) \tag{13}$$

$$h = \sqrt{a_2^2-\left(\frac{a-a_1}{2}\right)^2} \tag{14}$$

$$\lambda = \frac{(2a+a_1)(a+e)a_1a_2-\kappa_0 a^3(e-a_1)}{(a+a_1)[2a_2(a^2+aa_1+a_1^2)+a_1^3+\kappa_0 a^3]} \tag{15}$$

$$\kappa_0 = \left(\frac{t_s}{t_f}\right)^3 \tag{16}$$

2.4. The moment of inertia of crossbeams

The dimensions of a crossbeam section are shown in Fig. 3.

$$I_x = t_0 t_f y_G^2 + \frac{h_w^3 t_w}{12} + h_w t_w\left(\frac{h_w}{2}-y_G\right)^2 + b_{f1}t_{f1}(h_w-y_G)^2 \tag{17}$$

$$y_G = \frac{b_{f1}t_{f1}h_w+h_w t_w(h_w/2)}{t_0 t_f+b_{f1}t_{f1}+h_w t_w} \tag{18}$$

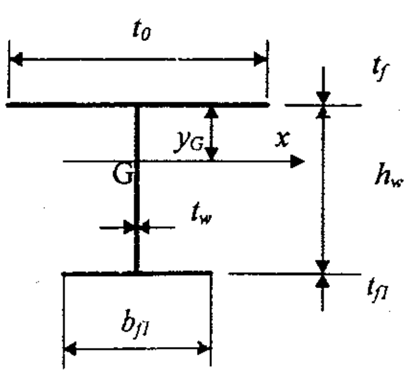

Fig. 3. Dimensions of a crossbeam section.

$t_0 = 0.917t$ approximately according to a Pelikan–Esslinger diagram, where t is the distance between crossbeams.

Note that the torsional stiffness of crossbeams can be neglected.

2.5. The bending moment of stiffeners at midspan

The homogeneous differential equation of an orthotropic plate, neglecting the bending stiffness in the transverse direction, can be written as

$$B_y\frac{\partial^4 w}{\partial y^4}+2H\frac{\partial^4 w}{\partial x^2\partial y^2}=0 \tag{19}$$

the solution of which is

$$w=[C_1\sinh(\alpha y)+C_2\cosh(\alpha y)+C_3\alpha y+C_4]\sin\frac{n\pi x}{b} \tag{20}$$

Considering the boundary conditions, the bending moment at midspan due to a concentrated force Q is given by

$$M_{00}=\varphi Qt\left\{\frac{1}{2\alpha^2 te_0}\left[1+\frac{\cosh[\alpha(t/2)-e_0)]}{\cosh(\alpha(t/2))}\right]+\frac{M_{0t}}{t}\left(1-\frac{\sinh(\alpha e_0)}{\alpha e_0}\,\frac{1}{\cosh(\alpha(t/2))}\right]\right\} \tag{21}$$

where Q = 50 kN/400 mm is the specific force (wheel load reduced to the plane of a stiffener). M_{00} is the specific bending moment acting in the plane of a stiffener. The bending moment acting ona stiffener is

$$M=M_{00}(a+e) \tag{22}$$

$$M_{0t}=\frac{\kappa_m}{a_t(1-\kappa_m)}\,\frac{1}{2\cosh(\alpha(t/2))}t \tag{23}$$

$$\kappa_m=-c+\sqrt{c^2-1} \tag{24}$$

$$a_t=-a_{11}B_y\alpha^2 t \tag{25}$$

$$a_{11}=-\frac{1}{B_y\alpha^2 t}\,\frac{\sinh(\alpha t)-\alpha t}{\sinh(\alpha t)} \tag{26}$$

$$a_{22}=-\frac{2}{B_y\alpha^2 t}\,\frac{\alpha t\cosh(\alpha t)-\sinh(\alpha t)}{\sinh(\alpha t)} \tag{27}$$

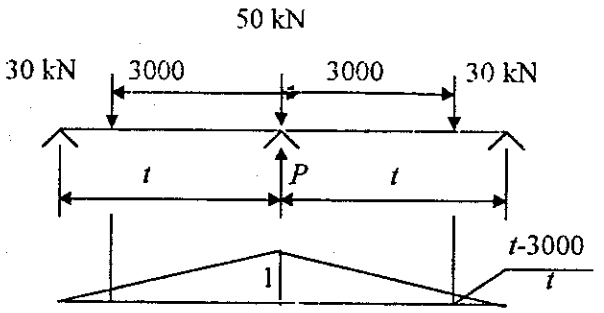

Fig. 4. Reactive force P acting on a crossbeam from wheel loads.

$$\alpha = \frac{n\pi}{b}\sqrt{\frac{2H}{B_y}} \quad n = 1, b \text{ is the width of the deck} \tag{28}$$

The dynamic factor can be calculated according to DIN 1072 [2] as

$$\varphi = 1.4 - j0.008\,\frac{t}{1000} - 0.1h_a \tag{29}$$

where h_a is the thickness of the asphalt layer.

2.6. *The bending moment of a crossbeam at midspan*

The reactive force from the wheel loads, according to Fig. 4, is

$$P = 50\ \text{kN} + \frac{2\times 30(t-3000)}{t} \quad \text{when } t > 3000\ \text{mm}$$

and

$$P = 50\ \text{kN} \qquad \text{when } t < 3000\ \text{mm}$$

In our numerical example we treat a bridge deck of width $b = 12$ m, thus we calculate with $8\varphi P$ (Fig. 5).

$$M_{max} = \varphi P b \tag{30}$$

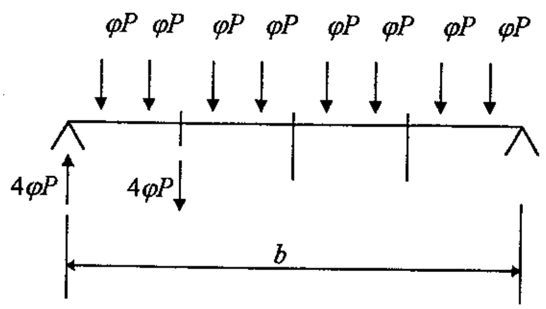

Fig. 5. Forces acting on a crossbeam.

2.7. *Fatigue constraint for stiffeners*

For bridge decks the fatigue constraint of welded joints is a governing factor. There are some recently published experimental research results in addition to the design categories defined by Eurocode 3 (EC3) [6–8]. Although the trapezoidal stiffeners can be prefabricated in a workshop and need not be splice welded on-site, we consider a site splice with a butt weld, no splice plate, with backing strip, full penetration, root gap > 4 mm, for which the recommended design category according to [8] is 80 MPa. Since this important joint is difficult to access for a test, we consider a safety factor according to EC3 of $\gamma_{Mf} = 1.35$. The spectrum factor can be taken as 1, the number of load cycles is 2×10^6.

The fatigue constraint is formulated as

$$\frac{M_{(n)}(a+e)}{I_y}(h - z_G) \le \frac{\Delta\sigma}{\gamma_{Mf}} = \frac{80}{1.35} \tag{31}$$

2.8. *Fatigue constraint for crossbeam*

$$\sigma_{max} = \varphi\,\frac{M_{max}}{I_x}(h_w - y_G) \le \frac{\Delta\sigma_1}{\gamma_{Mf}} \tag{32}$$

The fatigue stress range is 125 MPa, according to EC3, automatically welded continuous longitudinal fillet welds carried out from both sides with no stop/start positions. The safety factor can be taken as 1.15 for important accessible joints.

2.9. *Deflection constraints*

Deflection should be calculated without a dynamic factor. Stiffeners:

$$w_{max} = \frac{Pt^3}{48EI_y} \le w^* \tag{33}$$

According to Eurocode 3 Part 2 the allowable deflection is $w^* = 5$ mm. Crossbeams:

$$\frac{5p_{red}b^4}{384EI_x} \le w^* \tag{34}$$

where

$$p_{red} = \frac{8P}{b} \tag{35}$$

2.10. Local buckling constraint for stiffeners

According to Eurocode 3 Part 2

$$a_2 \le 38\varepsilon t_s \varepsilon = \sqrt{\frac{235}{f_y}} \tag{36}$$

f_y is the yield stress in MPa

2.11. Shear buckling constraint for crossbeam web

$$\frac{F_A}{h_w t_w} \le \frac{\tau_{ba}}{\gamma_{M1}} \quad F_A = 4\varphi P \tag{37}$$

where the partial safety factor for shear is

$$\gamma_{M1} = 1.1 \tag{38}$$

$$\gamma_w = \frac{h_w/t_w}{37.4\varepsilon\sqrt{K_\tau}} \quad k_\tau = 5.34 \tag{39}$$

$$\text{if } \lambda_w \le 0.8 \qquad \text{then } \tau_{ba} = \frac{f_y}{\sqrt{3}} \tag{40}$$

$$\text{if } 0.8 \le \lambda_w \le 1.2 \qquad \text{then } \tau_{ba} = \frac{f_y}{\sqrt{3}}[1 - 0.625(\lambda_w - 0.8)]$$

$$\text{if } \lambda_w \ge 1.2 \qquad \text{then } \tau_{ba} = \frac{0.9 f_y}{\lambda_w \sqrt{3}}$$

2.12. Frequency constraints

The stiffeners' first eigenfrequency is limited, according to Eurocode 3, Part 2 [7] to 2 Hz. The calculation of the eigenfrequency is as follows:

$$f_{1s} = \frac{\pi}{2t^2}\sqrt{\frac{EI_y}{m_s}} \tag{41}$$

The cross-sectional area of the stiffener and the deck plate is

$$A_s = a_1 t_s + 2a_2 t_s + (a+e)t_f \tag{42}$$

The mass of this part is

$$m_s = A_s \times 7.85 \times 10^{-6} + 60 \times 2.4 \times 10^{-6}(a+e) \tag{43}$$

where the thickness of the asphalt layer is 60 mm, density is 2.4×10^{-6} kg mm^{-3}.

The crossbeam's first eigenfrequency is also limited to 2 Hz. The calculation of the eigenfrequency is as follows:

$$f_{1c} = \frac{\pi}{2b^2}\sqrt{\frac{EI_x}{m_c}} \tag{44}$$

The cross-sectional area of the crossbeam and the deck plate is

$$A_c = t_0 t_f + b_{f1} t_{f1} + h_w t_w \tag{45}$$

The mass of this part is

$$m_c = A_c \times 7.85 \times 10^{-6} + 60 \times 2.4 \times 10^{-6} t_0 \tag{46}$$

2.13. Size limitations

According to Eurocode 3 Part 2

$e \le 25t_f$, e is the distance between stiffeners (Fig. 2) (47)

$t_s \ge 6$ mm

$t_f \ge 12$ mm

2.14. Formulation of a cost function according to the fabrication steps

The cost of a structure is the sum of the material and fabrication costs. The fabrication cost elements are the welding, cutting, preparation, assembly, tacking, painting costs, etc. It is very difficult to obtain such cost factors, which are valid all over the world, because there are great differences between the cost factors in highly developed and developing countries. If we choose the time as the basic data of a fabrication element we can handle this problem. The fabrication time depends on the technological level of the country and the manufacturer, but it is much closer to the real process to calculate with. After computing the necessary time for a fabrication work element, one can multiply by a specific cost factor, which can represent the development level differences. Although the whole production cost depends on many parameters and it is very difficult to express their effect mathematically, a simplified cost function can serve as a suitable tool for comparisons useful for designers and manufacturers [9,10].

The cost function can be expressed as

$$K = K_m + K_f = k_m V + k_f \sum_i T_i \tag{48}$$

where K_m and K_f are the material and fabrication costs, respectively, k_m and k_f are the corresponding cost factors, ρ is the material density, V is the volume of the structure, T_i are the production tiomes.

2.15. Fabrication times for welding

eqn (48) can be written in the following form:

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1+T_2+T_3) \tag{49}$$

where

$$T_1 = C_1 \Theta_d \sqrt{\kappa \rho V} \tag{50}$$

is the time for preparation, assembly and tacking, Θ_d is a difficulty factor, κ is the number of structural elements to be assembled.

$$T_2 = \sum_i C_{2i} a_{wi}^n L_{wi} \tag{51}$$

is the time of welding, a_{wi} is the weld size, L_{wi} is the weld length in mm, C_{2i} and n are constants given for different welding technologies.

$$T_3 = \sum_i C_{3i} a_{wi}^n L_{wi} \tag{52}$$

is the time of additional fabrication actions such as changing the electrode, deslagging and chipping.

The different welding technologies are as follows: SMAW (Shielded Metal Arc Welding), GMAW-C (Gas Metal Arc Welding with CO_2), SAW (Submerged Arc Welding).

Ott and Hubka [10] proposed that $C_{3i} = 0.3 C_{2i}$, so

$$T_2+T_3 = 1.3 \sum_i C_{2i} a_{wi}^n L_{wi} \tag{53}$$

Values of C_{2i} and n may be given according to COSTCOMP [11] as follows. COSTCOMP gives welding times and costs for different technologies [12]. To compare the costs of different welding methods and to show the advantages of automation, the manual SMAW, semi-automatic GMAW-C and automatic SAW methods are selected for fillet welds. The analysis of COSTCOMP data resulted in constants given in Fig. 6 and Tables 1, 2 and 3 for different joint types.

One can establish other fabrication components, calculate the fabrication time to even plates, the surface preparation time, the painting time, the cutting and edge grinding times, etc., but the main problem is how to formulate the equation concerning the time. The difficulty factor Θ_d represents that the welding or

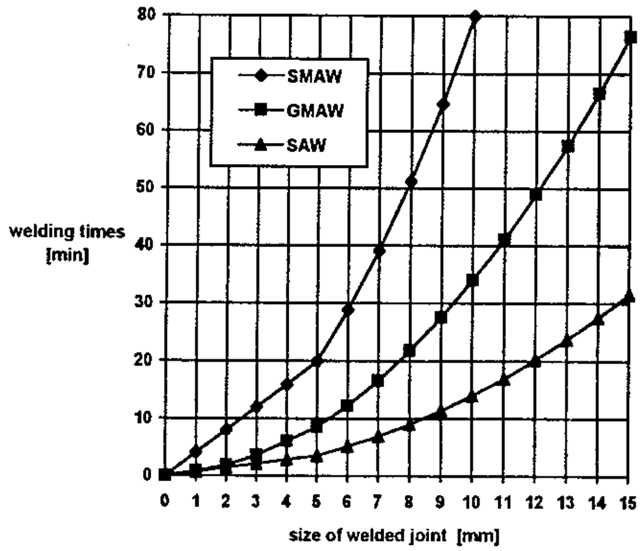

Fig. 6. Welding times for fillet welds of size a_w.

Table 1
Welding times T_2 (min) as a function of weld size a_w (mm) for longitudinal fillet welds in downhand position (see also Fig. 6)

Welding method	a_w (mm)	$10^3T_2 = 10^3C_2a_w^n$
SMAW	2–5	$4.0\ a_w$
	5–15	$0.7889\ a_w^2$
GMAW-C	2–5	$1.70\ a_w$
	5–15	$0.3394\ a_w^2$
SAW	2–5	$1.190\ a_w$
	5–15	$0.2349\ a_w^2$

Table 2
Welding times T_2 (min) as a function of weld size a_w (mm) for longitudinal 1/2 V butt welds in downhand position

Welding method	a_w (mm)	$10^3T_2 = 10^3C_2a_w^n$
SMAW	4–6	$2.7\ a_w$
	6–15	$0.45\ a_w^2$
GMAW-C	4–15	$0.1939\ a_w^2$
SAW	4–15	$0.1346\ a_w^2$

Table 3
Welding times T_2 (min) as a function of weld size a_w (mm) for longitudinal K-butt welds in downhand position

Welding method	a_w (mm)	$10^3T_2 = 10^3C_2a_w^n$
SMAW	5–16	$1.4029\ a_w^{1.25}$
GMAW-C	5–16	$0.129\ a_w^2$
SAW	5–16	$0.089\ a_w^2$

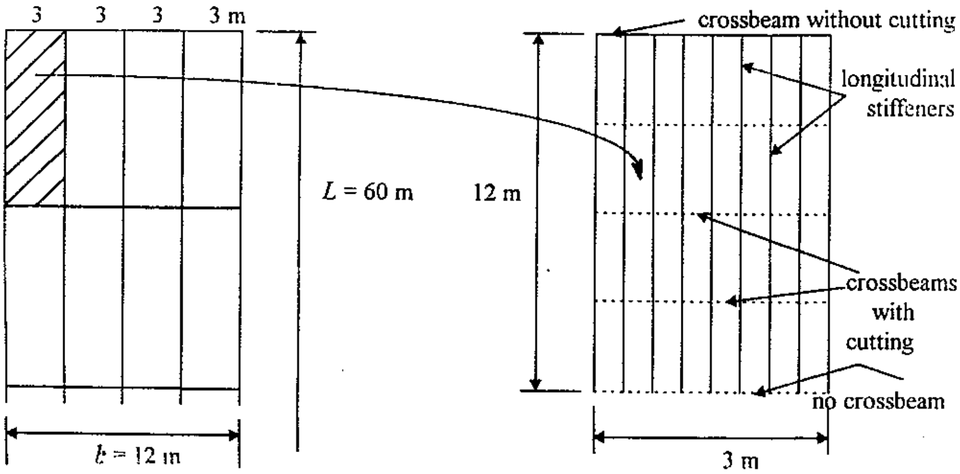

Fig. 7. The main dimensions of the bridge of our numerical example.

painting is overhead, or vertical, or horizontal and also the complexity of the structure. In our case we focused on welding costs [13–18]. The robot welding and some new technologies have different cost aspects [19,20].

The following formulae and values are used for the fabrication steps in our numerical example.

A complete bridge deck is constructed from structural elements of transportable dimensions [21]. In our numerical example a bridge of length $L = 60$ m and width $b = 12$ m is selected, composed from elements of dimensions $L_0 = 12$ m and $b_0 = 3$ m (Fig. 7).

2.15.1. Fabrication of 12×3 m elements in the workshop (Table 4)

(a) welding of stiffeners to deck plate with SAW fillet welds

$$C_2 = 0.2349 a_w^2, a_w = 1.25 t_s, L_w = 2\Phi_s \Phi t$$

Table 4
The place, type, cost, size and length of the welded joint for the fabrication of the 12×3 m elements in the workshop

Place of the joint	Welding technology	Cost parameter	Welded joint size	Welded joint length
Stiffener to deck plate	SAW	$0.2349\ a_w^2$	t_s	$2\Phi_s\Phi t$
Cutting	Normal acetylene	$1.1388 t_w^{0.25}$	t_w	$\Phi_s(a_1+2a_2)(\Phi-1)$
Crossbeam lower flange to web	SAW	$0.2349\ a_w^2$	$0.5\ t_w$	$2\Phi_s\Phi t$
Crossbeam web to deck plate	GMAW	$0.3394\ a_w^2$	$1.25\ t_w$	$(e+2a_2)\Phi_s 2(\Phi-0.5)$

Table 5
The place, type, cost, size and length of the welded joint for the fabrication of the whole deck on-site

Place of the joint	Welding technology	Welding cost parameter	Welded joint size	Welded joint length
Stiffeners to end crossbeams	GMAW	$0.3394\ a_w^2$	$1.25\ t_s$	$\frac{b}{b_0}\frac{L}{L_0}(a_1+2a_2+e)\Phi_s$
Longitudinal and transverse splices	SAW	$0.2349\ a_w^2$	t_f	$\left(\frac{b}{b_0}-1\right)b$
Web splices	GMAW	$0.3394\ a_w^2$	t_w	$\left(\frac{b}{b_0}-1\right)\left(\frac{L}{L_0}+1\right)$
Flange splices	GMAW	$0.3394\ a_w^2$	t_{f1}	$\left(\frac{b}{b_0}-1\right)\left(\frac{L}{L_0}+1\right)$

(b) cutting the crossbeam webs excluding the end crossbeam

$$C_2 = 1.1388t^{0.25}, t = t_w, L_w = \Phi_s(a_1+2a_2)(\Phi-1)$$

(c) welding of crossbeam lower flanges to webs with SAW fillet welds

$$C_2 = 0.2349a_w^2, a_w = 0.5t_w, L_w = 2\Phi_s\Phi t$$

(d) welding of crossbeam webs to deckplate and to stiffeners with GMAW fillet welds

$$C_2 j = 0.3394a_w^2, a_w = 1.25t_s, L_w = (e+2a_2)\Phi_s 2(\Phi-0.5)$$

The volume of an element in which the number of stiffeners is $\Phi_s = b_0/(a+e)$ and the number of crossbeams is $\Phi = L_0/t$ can be expressed as

$$V_1 = \Phi_s(a_1+2a_2)t_s\Phi t + b_0\Phi t t_f + (h_w t_w + A_f)\Phi b_0 \quad (54)$$

The number of assembled elements is

$$\kappa_1 = \Phi_s + \Phi + 1 \quad (55)$$

Table 6
The minimum cost of bridge deck for different crossbeam distances in the case of normal steel and cost factors ratio = 0.5 kg min⁻¹

t (mm)	Total cost ($)	Material cost ($)	Fabrication cost ($)
1000	401316	308450	92866
1500	346586	241964	105322
2000	286217	195269	90948
2500	265008	169201	95807
3000	257182	172032	85150
3500	273337	171888	101449
4000	285208	175926	109282
4500	295913	173239	122674

The cost function for an element can be written as

$$\frac{K_1}{k_m} + \rho V_1 + \frac{k_f}{k_m}\left\{\Theta_{ds}(\kappa_1\rho V_1) + 1.3\left[C_{2SAW}(0.5t_w)^n 2b_0\Phi + C_{2CUT}t_w^2\Phi_s(a_1+2a_2)(\Phi-1) + \ldots\right]\right\}$$
$$\times\left\{\left[\ldots + C_{2SAW}(1.25t_s)^n(e+2a_2)\Phi_s 2(\Phi-0.5)\right]\right\} \quad (56)$$

2.15.2. Fabrication of the whole deck structure on-site (Table 5)

(a) welding of stiffeners to end crossbeams with GMAW fillet welds

$$C_{2GMAW} = 0.3394a_w^2 a_w = 1.25t_s, L_w = \frac{b}{b_0}\frac{L}{L_0}(a_1+2a_2+e)\Phi_s$$

(b) welding of the longitudinal and transverse splices with SAW butt welds

$$C_{2SAW} = 0.2349a_w^2 a_w = t_f, L_w = \left(\frac{b}{b_0}-1\right)b$$

(c) welding of crossbeam web and lower flange splices (these splices can also be realized by using bolted connections) with GMAW butt welds

- web splices

$$C_{2GMAW} = 0.3394a_w^2, a_w = t_w, L_w = \left(\frac{b}{b_0}-1\right)\left(\frac{L}{L_0}+1\right)$$

Table 7
The minimum sizes of bridge deck-plate, floor beam and stiffener with different crossbeam distance with normal steel and cost factors ratio = 0.5 kg min⁻¹

t (mm)	t_f	h_w	t_w	A_f	t_s	Total cost ($)	
1000	23.27	1418.50	10.23	1220.00	6.00	401316	Continuous
	23	1410	11	1220	6	416321	Discrete
1500	17.08	1400.87	11.93	688.07	6.04	346586	Continuous
	17	1400	12	690	6	344730	Discrete
2000	13.99	1424.09	11.02	644.14	5.99	286217	Continuous
	14	1430	11	640	6	286572	Discrete
2500	12.16	1382.23	11.83	780.83	6.00	265008	Continuous
	12	1380	12	780	6	266552	Discrete
3000	12.20	1382.06	11.37	768.75	6.44	257182	Continuous
	13	1390	11	760	7	274168	Discrete
3500	12.19	1454.73	11.51	750.00	6.84	273337	Continuous
	12	1450	12	750	7	283254	Discrete
4000	12.67	1531.30	11.50	759.49	7.70	285208	Continuous
	12	1530	12	750	8	315103	Discrete
4500	12.56	1536.08	12.13	886.22	7.50	295913	Continuous
	12	1530	13	880	8	325290	Discrete

- flange splices

$$C_{2GMAW}=0.3394a_w^2, a_w=t_{f1}, L_w=\left(\frac{b}{b_0}-1\right)\left(\frac{L}{L_0}+1\right)$$

The volume of the whole deck structure is

$$V_2=\kappa_2 V_1 \tag{57}$$

$$\kappa_2=\frac{bL}{b_0 L_0} \tag{58}$$

The cost function of the whole deck structure is

$$\frac{K_2}{k_m}=\frac{k_f}{k_m}\left\{\Theta_{d_2}(\kappa_2\rho V_2)+1.3\left[C_{2GMAW}(1.25t_s)^n\frac{b}{b_0}\frac{L}{L_0}\right.\right.$$

$$\left.\left.\times(a_1+2a_2+e)\Phi_s+C_{2SAW}t_f^2\left[\left(\frac{b}{b_0}-1\right)b\right]+\ldots\right]\right\}$$

$$\left\{\left[\ldots+C_{2GMAW}(h_w t_w^n+b_{f1}t_{f1}^n)\left(\frac{b}{b_0}-1\right)\left(\frac{L}{L_0}+1\right).\right]\right\} \tag{59}$$

The whole cost function to be minimized is

$$\frac{K}{k_m}=\frac{20K_1+K_2}{k_m} \tag{60}$$

2.16. The optimization procedure for the numerical example

The cost function (eqn (60)) is to be minimized considering the following constraints: eqn (31)eqn (32)eqn (33)eqn (34)eqn (36)eqn (37)eqn (41).

2.17. Size limitations

The variables are as follows: t_f, t_s, h_w, t_w, $A_{f1}=b_{f1}\cdot t_{f1}$, which are optimized for a series of discrete values of t to obtain t_{opt} corresponding to K_{min}.

$12\leq t_f\leq 28$ mm

$300\leq h_w\leq 2000$ mm

$8\leq t_w\leq 25$ mm

$200\leq A_{f1}\leq 1600$ mm^2

$6\leq t_s\leq 20$ mm

3. Results and conclusions

The optimization is performed with the following data: steel yield stress $f_y=235$ MPa; cost ratio

Table 8
The minimum cost of bridge deck for different crossbeam distances in the case of normal steel and cost factors ratio = 1.0 kg min^{-1}

t (mm)	Total cost ($)	Material cost ($)	Fabrication cost ($)
1000	472090	305791	166299
1500	366088	239407	126681
2000	3415464	223607	117894
2500	319302	202949	116353
3000	315379	197231	118148
3500	387922	218043	169880
4000	437446	222948	214498
4500	470368	221026	249341

Table 9
The minimum sizes of bridge deck-plate, floor beam and stiffener with different crossbeam distance with normal steel and cost factors ratio = 1.0 kg min^{-1}

t (mm)	t_f	h_w	A_f	t_s	Total cost ($)		
1000	12.48	1539.08	8.33	1042.93	5.99	472090	Continuous
	12	1530	9	1040	6	486507	Discrete
1500	12.38	1561.57	9.59	1039.67	6.00	366088	Continuous
	12	1560	10	1030	6	384232	Discrete
2000	12.00	1538.95	8.00	1051.15	6.00	341564	Continuous
	12	1540	8	1050	6	340840	Discrete
2500	12.00	1535.02	8.00	997.16	6.00	319302	Continuous
	12	1540	8	990	6	319977	Discrete
3000	12.00	1542.40	8.00	911.40	6.38	315379	Continuous
	12	1540	8	920	7	349154	Discrete
3500	13.37	1543.00	9.76	846.56	7.05	387922	Continuous
	13	1540	10	840	7	389882	Discrete
4000	12.20	1544.60	11.16	808.43	7.17	437446	Continuous
	12	1540	12	800	8	487249	Discrete
4500	12.45	1540.87	12.19	888.78	7.40	470368	Continuous
	12	1550	12	880	8	477663	Discrete

$k_f/k_m = 0$–2, there are five unknown variables as follows:

$$x_1 = t_f, x_2 = h_w, x_3 = t_w, x_4 = A_f = b_{f1}t_{f1}, x_5 = t_s \quad (61)$$

(0D)The number of constraints for the crossbeam is 5, for the stiffener is 3 according to eqn (31)eqn (32)eqn (33)eqn (34)eqn (36)eqn (37)eqn (41) and eqn (44) and size limitations eqn (47). The mathematical optimization technique is the Rosenbrock's Hillclimb procedure [2]. The results for normal steel, $f_y = 235$ MPa, and cost ratio $k_f/k_m = 0.5$ can be seen in Table 6 and the discrete values in Table 7. The results for normal steel, $f_y = 235$ MPa, and cost ratio $k_f/k_m = 1.0$ can be seen in Table 8 and Table 9. The results for normal steel, $f_y = 235$ MPa, and cost ratio $k_f/k_m = 2.0$ can be seen in Table 2 and Table 11.

The results show that the optimum distance between crossbeams for $k_f/k_m = 0.5$ is about $t_{opt} = 3000$ mm, for $k_f/k_m = 1.0$ is $t_{opt} = 3000$ mm and for $k_f/k_m = 2.0$ is $t_{opt} = 2500$ mm. The higher fabrication cost results in closer crossbeams, which means weaker stiffeners.

The ratio between material and the fabrication costs over the total cost for the ratio $k_f/k_m = 0.5$ ratio is about 66–34%, for $k_f/k_m = 1.0$ is 62–38%, and for $k_f/k_m = 2.0$ is 52–48% respectively. If we optimise the bridge deck for the minimum weight, the optimum distance between crossbeams is 3000, 3000 and 2500–3500 mm for $k_f/k_m = 2.0$, 1.0 and 0.5 respectively. Greater costs have greater effect on the optimum dimensions. If the crossbeams are closer to each other, the stiffeners and deck plate can be thinner reducing the welding cost, and this effect is greater than the increase of costs of more crossbeams. Using higher strength steel of $f_y = 355$ MPa, for $k_f/k_m = 2.0$ the optimum crossbeam distance is $t_{opt} = 2000$ mm, instead of 2500 mm. It means that the increase of yield stress decreases the distance between crossbeams, since the program cannot reduce the thickness of the stiffeners because of the size limit.

We have fixed the minimum stiffener thickness to 6 mm. If we decrease this limit to 4 mm, the distance of crossbeams becomes smaller due to the smaller stiffener costs. The active constraints are usually the fatigue and deflection ones.

The computer program developed runs on a Pentium PC, under the MS Fortran Power Station Developing System. The user interface is made by MS Visual Basic. One runtime is a few minutes. The calculation contains the discretization after finding the continuous values. This is very important for the fabrication. The computer calculation shows that this program is useful for the predesign of bridge decks, taking into account fatigue, stability, deflection and frequency constraints.

Table 10
The minimum cost of bridge deck for different crossbeam distances in the case of normal steel and cost factors ratio = 2.0 kg min^{-1}

t (mm)	Total cost ($)	Material cost ($)	Fabrication cost ($)
1000	658334	394309	264025
1500	594357	322029	273328
2000	551351	286062	265289
2500	546181	282837	263344
3000	564586	271349	293237
3500	654340	277697	376643
4000	704468	310165	394303
4500	703493	286607	416886

Table 11
The minimum sizes of bridge deck-plate, floor beam and stiffener with different crossbeam distance with normal steel and cost factors ratio = 2.0 kg min^{-1}

t (mm)	t_f	h_w	t_w	A_f	t_s	Total cost ($)	
1000	12.37	1638.43	8.00	885.06	6.00	658334	Continuous
	13	1630	8	880	6	662878	Discrete
1500	12.00	1680.00	8.02	414.15	6.00	594357	Continuous
	12	1690	8	410	6	596605	Discrete
2000	12.00	1657.70	8.00	417.36	6.00	551351	Continuous
	12	1660	8	410	6	551610	Discrete
2500	12.00	1653.76	8.00	362.2	5.99	546181	Continuous
	12	1660	8	360	6	547985	Discrete
3000	12.30	1585.30	8.74	328.00	6.46	564586	Continuous
	12	1590	9	320	7	637696	Discrete
3500	12.04	1575.43	10.29	434.33	6.66	654340	Continuous
	12	1550	11	350	7	740251	Discrete
4000	12.12	1794.90	8.78	372.85	6.947	669187	Continuous
	12	1790	9	370	7	658372	Discrete
4500	12.45	1540.87	12.19	888.78	7.40	703493	Continuous
	12	1500	12	880	8	793937	Discrete

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